# Latest Bernese advances in Lunar geodesy

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# Outline

Lunar Geodesy

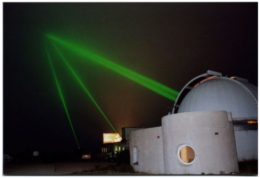
GRAIL @ AIUB

- Observables and modeling
- Orbit recovery
- Gravity field determination
- GRAIL+LLR

Conclusions

Le Cosmicomiche, I. Calvino
Credits: Gianni De Conno

# Lunar Geodesy

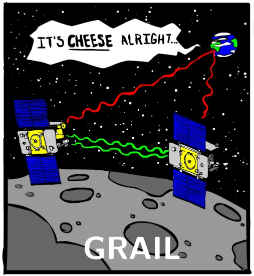


**LLR**

rotation, librations, distance

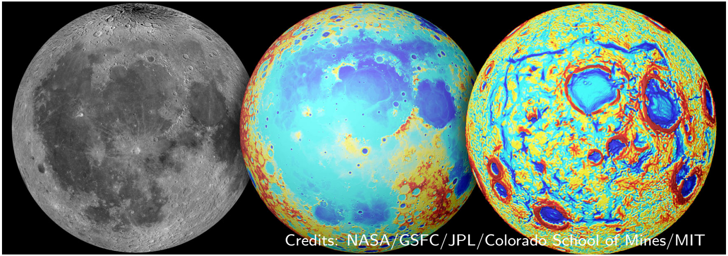
**LRO**

topography, rotation



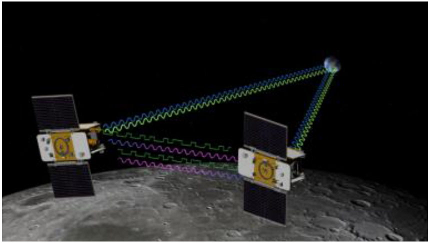

**GRAIL**

gravity, tides



Credits: NASA/GSFC/JPL/Colorado School of Mines/MIT

# The GRAIL mission



## GRAIL

(Gravity Recovery and Interior Laboratory)

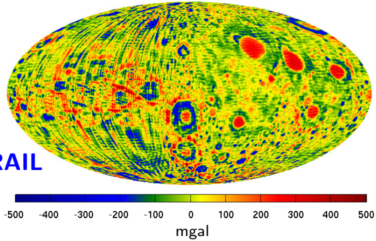
M.T. Zuber et al, Science, 2013

March - December 2012

Polar orbit, altitude 25-50 km

- Understand the internal structure and history of the Moon
- Homogeneous coverage of the far side (GRACE heritage)

**pre-GRAIL**

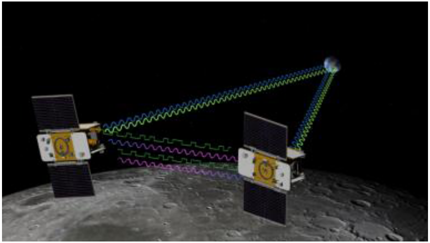



**pre-GRAIL solutions:**

LP165A (Lunar Prospector)

SGM150J (Selene)

# The GRAIL mission



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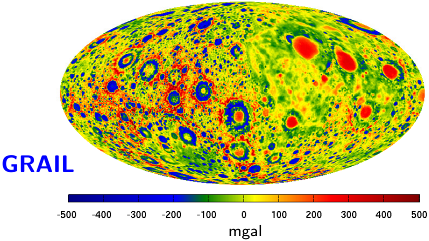
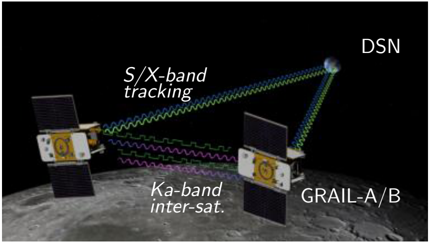



**Latest NASA solutions:**

GL1500E (JPL)

GRGM1200A (GSFC)

# The GRAIL mission: Satellite signals




- S-band two-way link ($2.3$ GHz)
- X-band one-way link ($8.4$ GHz)

**One-way X-band Doppler (nominal $0.08$ mm/s):**
- emission/reception by different clocks
- smaller onboard antenna

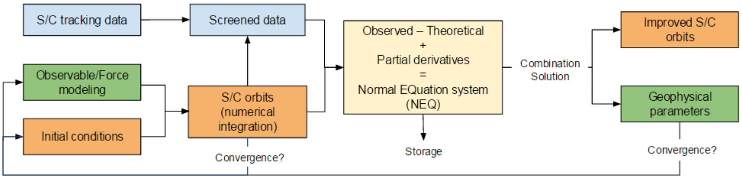
**Two-way S-band Doppler (nominal $0.3$ mm/s):**
- emission/reception by the same clock (DSN)
- larger onboard antenna

**Ka-Band Range Rate (KBRR) (nominal $0.03\mu$m/s):**
- Derived from Lunar Gravity Ranging System one-way phases

# The Celestial Mechanics Approach (CMA)

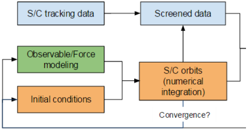
Within the Bernese GNSS Software (BSW):

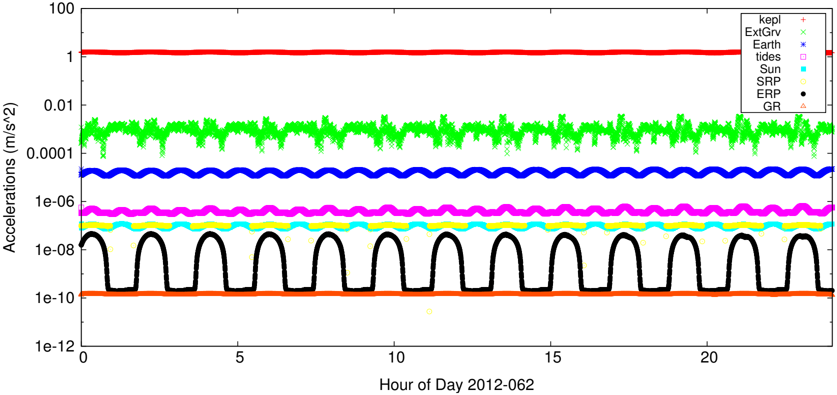
- Numerical integration (with a priori parameters) of equations of motion and variational equations.
- Set up of normal equations (NEQs) **for each observation type** (Doppler, KBRR, positions, ...) on a daily basis.
- Combination of the NEQs with appropriate weighting.
- NEQ manipulation (e.g., preelimination of parameters and accumulation to weekly, monthly, etc... NEQs )
- NEQ inversion → simultaneous solution for the improved parameters (orbit, gravity field coefficients, etc...)



# Orbit propagation

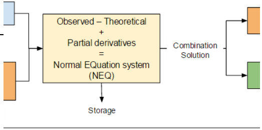
- Daily arcs, initial conditions from GNI1B science orbits
- Force model (SGM150J and GRGM900C up to d/o 600 a priori)



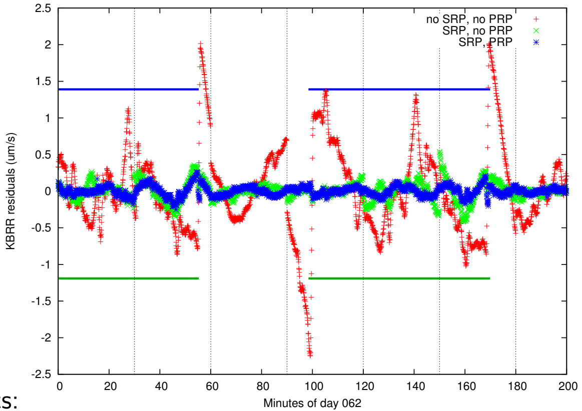
# Parameter estimation

| Observation | nObs | error | weight |
|---|---|---|---|
| 2-way Doppler | 416746 | 0.3 mm/s | 1 |
| 1-way Doppler | 334181 | 0.08 mm/s | 0.1 |
| KBRR | 1261440 | 0.03 $\mu$m/s | $10^8$ |




| Parameter | | R | S | W |
|---|---|---|---|---|
| **Arc-specific** | | | | |
| $x_0, v_0$ | 6 | | | |
| emp. accel. | opr | $\times$ | | |
| pulses | 30' | 0 | 1 $\mu$m/s | 1 $\mu$m/s |
| **Global** | | | | |
| Gravity field coeff. | $\times$ | | | |
| Love number $k_2$ | $\times$ | | | |

# Orbit determination: KBRR residuals

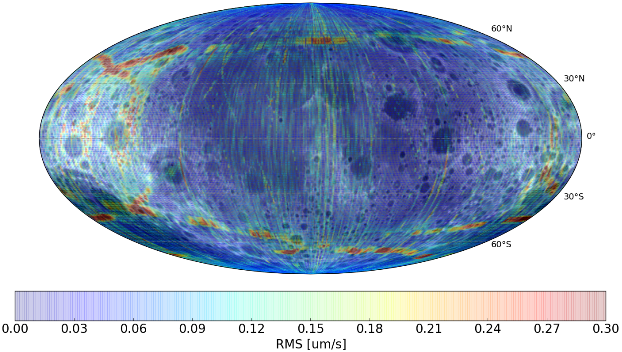



Visible effects:

- impact of the pseudo-stochstic pulses (every 30');
- solar radiation pressure at light/shadow transitions.

**Based on GRGM900C, d/o 600**

# Orbit determination: KBRR residuals

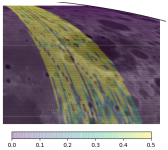


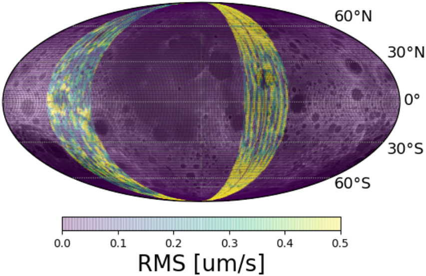

Visible effects:

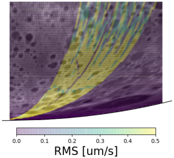
- impact of the pseudo-stochstic pulses (every 30’);
- solar radiation pressure at light/shadow transitions.

Huge improvement from additional SRP and PRP modeling!!

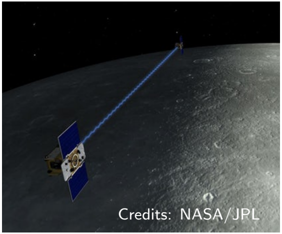
# Orbit determination: improved eclipses



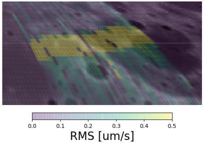



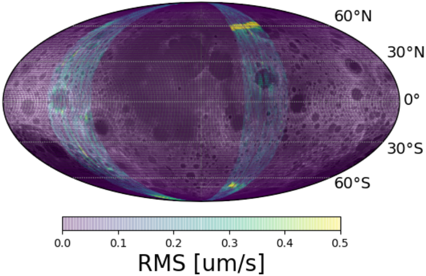



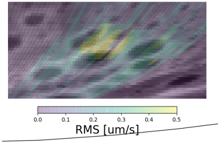

## No SRP, ERP
## (pulses + empirical only)



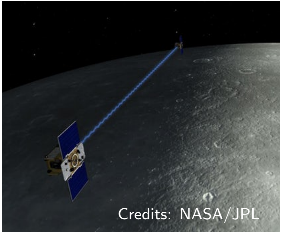
# Orbit determination: improved eclipses



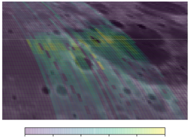



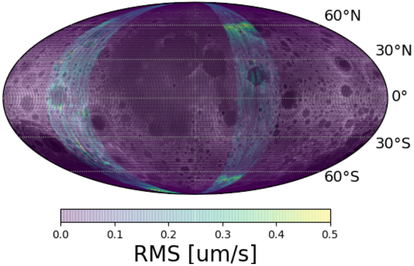



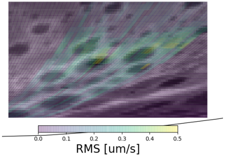

## SRP + ERP



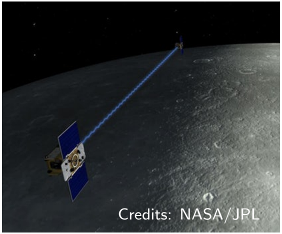
# Orbit determination: improved eclipses



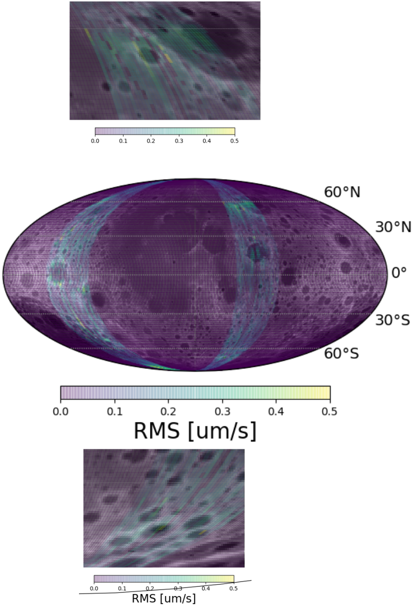


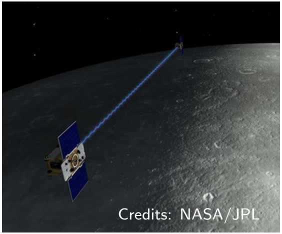

## Solar Panel Current based



# Orbit determination: improved eclipses

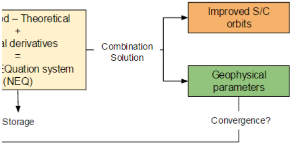


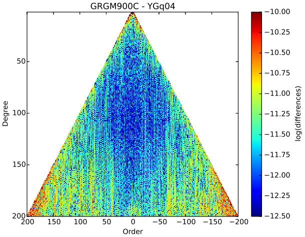

## Solar Panel + Time Shift



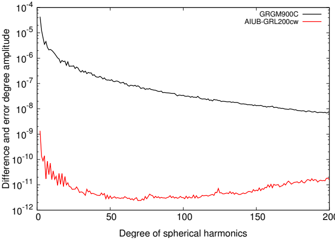
# Gravity field determination

- **A priori orbit: fit of Doppler and KBRR observations with appropriate parametrization**
- Combination with KBRR daily NEQs
- NEQs stacking up to the whole mission (pre-elimination of orbit parameters)
- NEQs inversion and solution



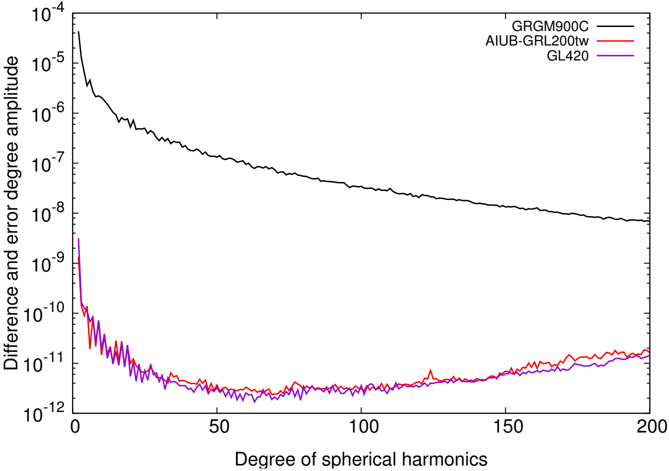

$\longrightarrow$




$$V(r,\lambda,\phi) = \frac{GM_M}{r} \sum_{l=1}^{l_{\max}} \left(\frac{R_M}{r}\right)^l \sum_{m=0}^{l} \bar{P}_{lm}(\sin\phi)\left(\bar{C}_{lm}\cos m\lambda + \bar{S}_{lm}\sin m\lambda\right)$$

# Gravity field determination: GRGM900C

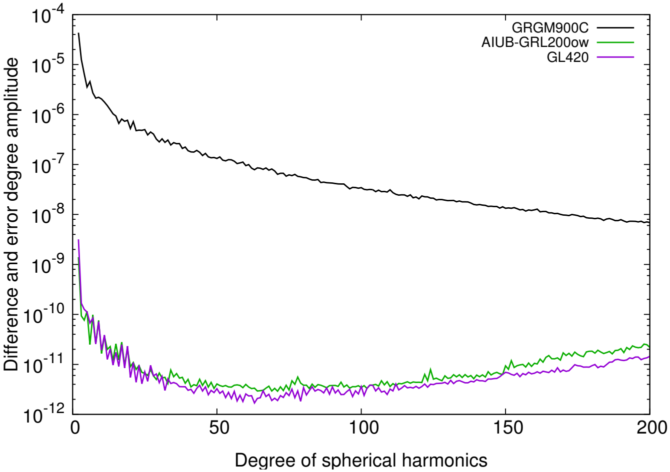
Difference degree amplitudes : $\Delta_l = \sqrt{\frac{1}{2l+1} \sum_{m=0}^{l} \left(\Delta\bar{C}_{lm}^2 + \Delta\bar{S}_{lm}^2\right)}$




a priori GRGM900C (d/o 660): 2-way Doppler + KBRR

# Gravity field determination: GRGM900C

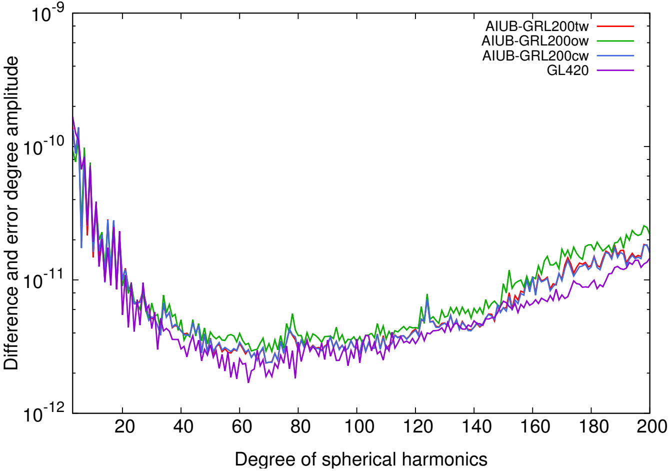
Difference degree amplitudes : $\Delta_l = \sqrt{\frac{1}{2l+1} \sum_{m=0}^{l} \left(\Delta \bar{C}_{lm}^2 + \Delta \bar{S}_{lm}^2\right)}$




a priori GRGM900C (d/o 660): 1-way Doppler + KBRR

# Gravity field determination: GRGM900C

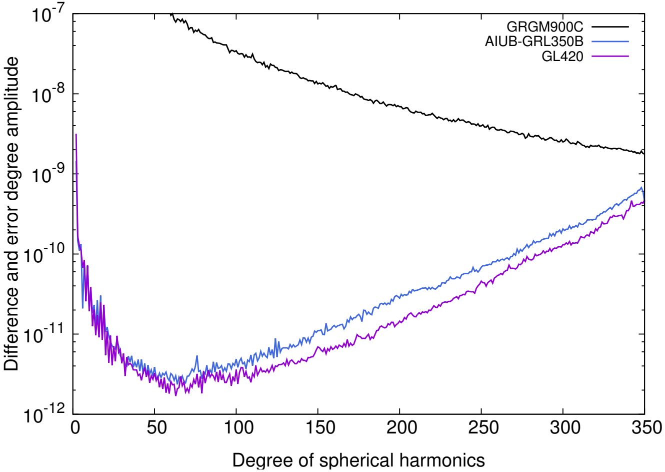
Difference degree amplitudes : $\Delta_l = \sqrt{\frac{1}{2l+1}\sum_{m=0}^{l}\left(\Delta\bar{C}_{lm}^2 + \Delta\bar{S}_{lm}^2\right)}$




**NEQ Combination:**
$0.1\times$ 1-way $+$
$1\times$ 2-way $+$
$10^8\times$ KBRR

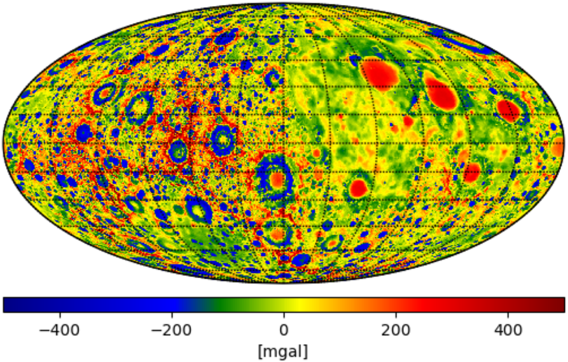
# Gravity field determination: GRGM900C

Difference degree amplitudes : $\Delta_l = \sqrt{\frac{1}{2l+1} \sum_{m=0}^{l} \left( \Delta\bar{C}_{lm}^2 + \Delta\bar{S}_{lm}^2 \right)}$



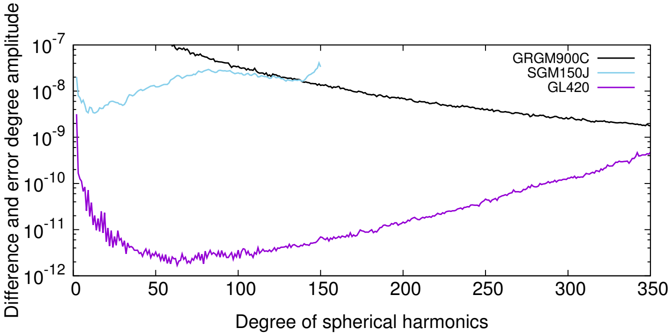
# Gravity field determination: GRGM900C

## Gravity field anomalies AIUB-GRL350B

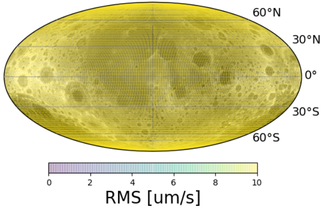


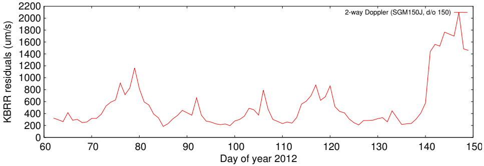

| Solution | $k_2 \pm \sigma$ |
|---|---|
| **AIUB-GRL350B** | $0.024147 \pm 0.000069$ |
| **GRGM900C** | $0.024116 \pm 0.000108$ |

# Gravity field determination: SGM150J




a priori SGM150J



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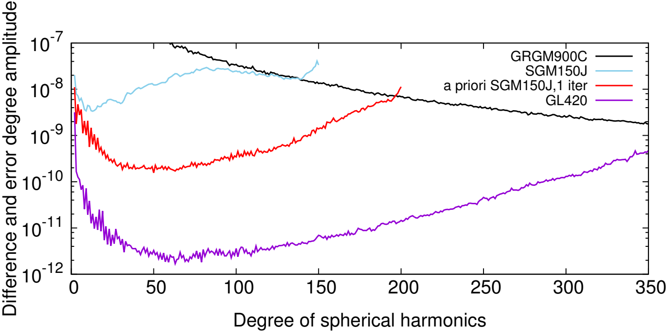
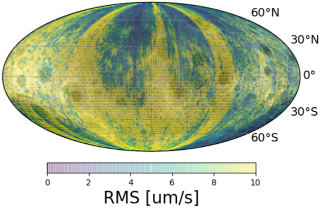
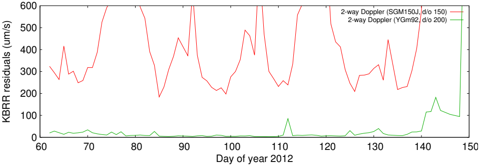



a priori SGM150J

1 iteration: April



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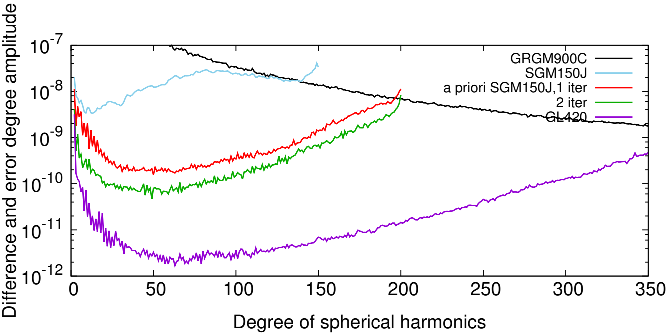
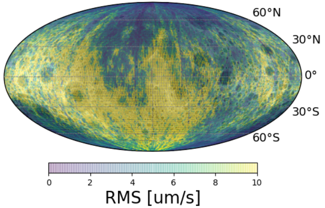
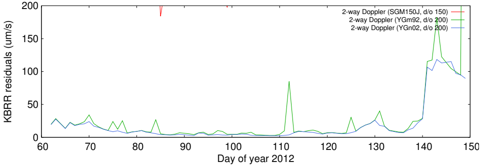
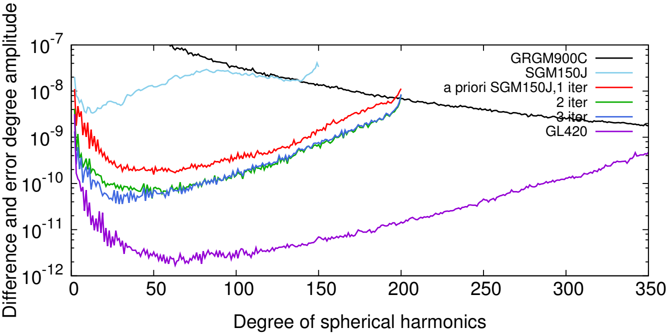



a priori SGM150J
1 iteration: April
2 iteration: 62-140



# Gravity field determination: SGM150J



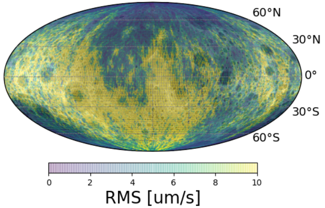

a priori SGM150J

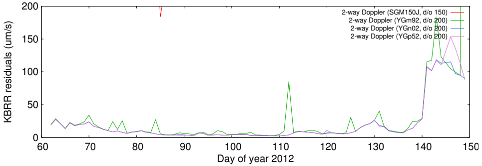
1 iteration: April

2 iteration: 62-140

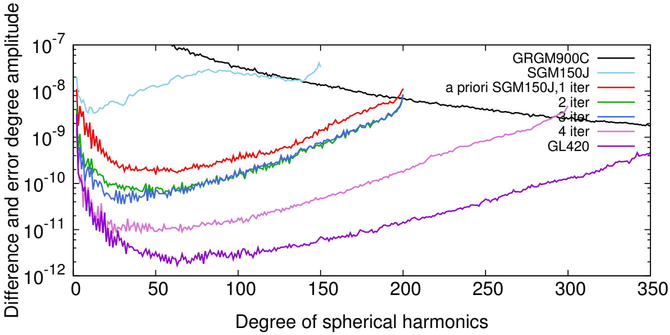
3 iteration:

SRP+PRP modeling



# Gravity field determination: SGM150J




a priori SGM150J

1 iteration: April

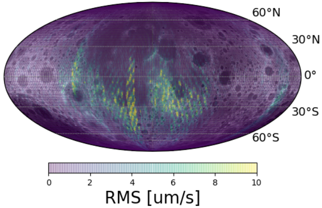
2 iteration: 62-140

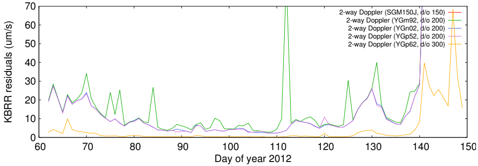
3 iteration:

SRP+PRP modeling

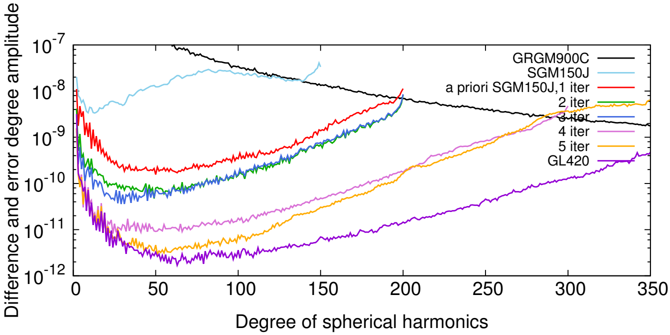
4 iteration:

larger param. space

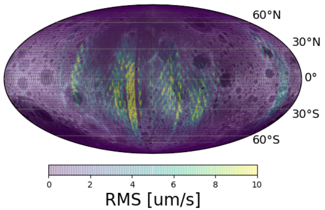


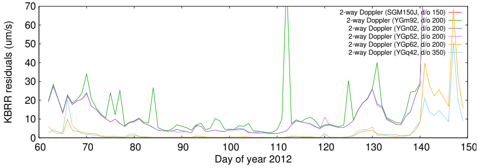



# Gravity field determination: SGM150J




a priori SGM150J
1 iteration: April
2 iteration: 62-140
3 iteration:
SRP+PRP modeling
4 iteration:
5 iteration: 62-149
larger param. space



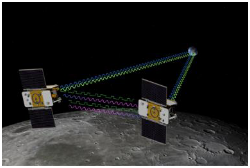



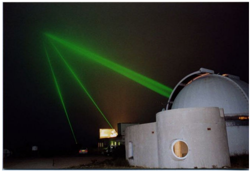
# GRAIL + Lunar Laser Ranging

Combination of techniques ⇒ Optimal solutions for geophysics

- GRAIL (AIUB) + LLR (POLAC@SYRTE)

Collaboration with A. Bourgoin





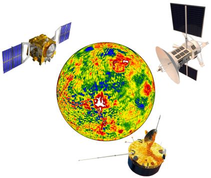
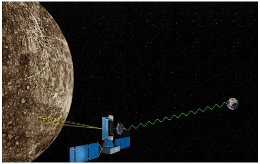
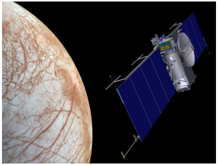
Gravity field, tides, rotation

Low degrees gravity field, tides, rotation, Earth/Moon distance

- Combination on NEQ level (full covariance information)
- Different geometries ⇒ different sensitivity
- Similar principle as GRACE + SLR on Earth
- **Current status:** combined gravity + $k_2$

# Conclusions

- Bernese GNSS Software capable of 1-way and 2-way DSN Doppler data → **inhouse** processing of planetary mission data
- Parallelized MKL/Lapack environment for large solutions
- Final Moon gravity field (and tides) solution on track
- Collaborations and ongoing projects in planetary geodesy @ AIUB

| Venus | Mercury | Europa |
|---|---|---|
|  |  |  |


Credits: JAXA (Selene)

Thanks for your attention!
Questions?

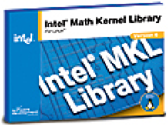
# LAPACK/INTEL MKL

- High resolution Moon gravity fields = high computational needs
- Parallel code for gravity NEQ setup (NEQSYS2) + inversion (NEQSOLVE)

| d/o | n. of parameters | standard | MKL |
|---|---|---|---|
| 200 | 40397 | $\approx$ 1 week | $\approx$ 1 day ($20'$ Y) |
| 300 | 90527 | $\approx$ 2.5 week | $\approx$ 3 days ($1.5$ h Y) |
| 350 | 123000 | - | $\approx$ 1 week ($3.5$ h Y) |

UBELIX

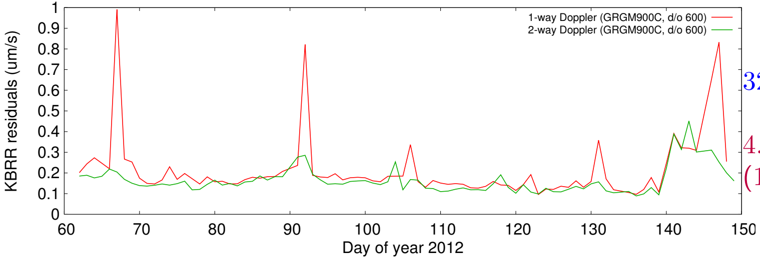
+




Parallel Intel MKL/LAPACK libraries for optimal use of parallel UniBE HPC Cluster (UBELIX) environment

# Combined orbit: KBRR residuals

$0.68 mm/s$




$32\ \mu m/s$

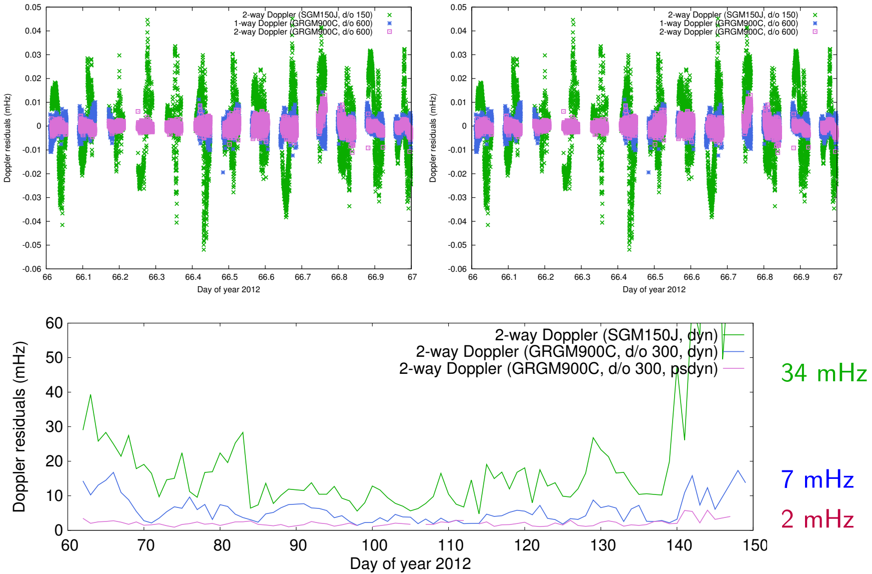
$4.6\ \mu m/s$

$(1.7\ \mu m/s)$

Daily RMS values of KBRR residuals for GRAIL-A (PM), using different gravity field models and parametrizations.

- Days $140 - 150$ at lower altitude $\rightarrow$ larger residuals

# Observed vs computed : Doppler residuals



# Non-gravitational forces: setup

- Solar Radiation Pressure (28-plates macromodel, Fahnestock 2012)

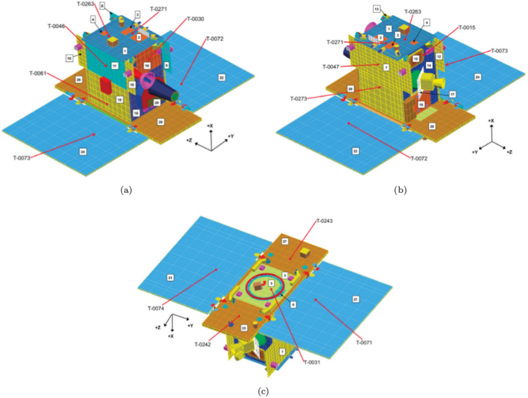
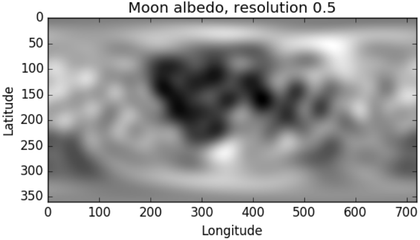


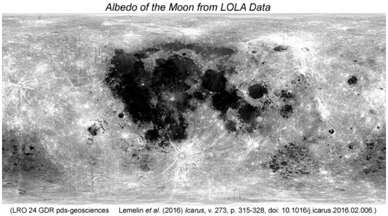

Figure 1. Placement of surfaces on GRAIL-B in highest fidelity model.

# Non-gravitational forces: setup

- Solar Radiation Pressure (28-plates macromodel, Fahnestock 2012)
- Moon Albedo (Delft Albedo Model-1, d/o 15)




Delft Albedo Model-1, d/o 15




- Moon IR (black body)

LOLA lunar albedo map